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Cooling Effects of Preferred Air Velocity in Muggy Conditions

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Preferred air velocity was investigated by testing a total of 241 *Japanese subjects under different air temperatures and humidities in a climate chamber. The work was done to encourage energy efficient air-conditioning design. Increases in air temperature and relative humidity were compensated by increases in preferred air velocity, and then the subjects reported themselves both slightly cool and comfortable. In addition, differences in preferred air velocity with seasonal variation, individual variation, age and sex were examined. © 1997 Elsevier Science Ltd.*

INTRODUCTION

THE Japanese summer is muggy and uncomfortable. Air movement can provide thermal comfort and freshness in muggy conditions. It is a desirable way to provide thermal comfort because it can be very energy efficient.

The purpose of this study is to investigate subjects' preferred air velocity in muggy conditions, and the upper and lower limits of air temperatures at which thermal comfort can be obtained with the preferred air velocity. Such information is useful for air-conditioning design in that an increase of air temperature and humidity is compensated by an increase of air velocity.

Previous studies of the preferred air velocity at different air temperatures have been published: McIntyre investigated preferred air velocity in the range of 22–30°C [1] and Tanabe investigated in the range 22–32°C [2], but they did not investigate preferred air velocity at different humidities.

In the present study, we experimentally investigate preferred air velocity for thermal comfort in hot and humid conditions such as those of the Japanese summer, and the physiological and psychological effects of preferred air velocity. We investigate the variation of preferred air velocity with seasonal variation, individual variation, age and sex.

Three experiments are combined, as follows.

Experiment 1: the preferred air velocity in muggy conditions and the physiological and psychological effects of preferred air velocity.

Experiment 2: seasonal variation and individual variations of preferred air velocity.

Experiment 3: difference in preferred air velocity by age and sex.

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EXPERIMENTAL DESIGN

Experimental facilities

The experiments took part in climate chamber A (5.25 m × 5.25 m × 2.5 m) or B (3 m × 3 m × 2.4 m) in Nara Women's University. Airflow apparatus which was able to generate air movement of different velocities was located in the chamber. The airflow apparatus was located 80–100 cm from the subject.

Subjects and clothing

Young female subjects took part in experiments 1 and 2. Old male and old female subjects, and young male subjects took part in experiment 3. The young subjects were healthy and between 19 and 25 years old. The old subjects were between 65 and 80 years old, and they were healthy and active. All subjects were volunteers and were paid for participating.

The female subjects were clothed in a summer uniform which we prepared: T-shirts (half-sleeves), skirt (shin, bias flair, knee length), stockings, and their own panties and brassieres. The clothing insulation value was estimated at 0.3 clo following the ISO Standard [3]. The male subjects were clothed in a male summer uniform: T-shirts, trousers, socks, and their own briefs. The clo-value of clothing was estimated at 0.4 clo. Four old male and three old female subjects were dressed in underwear with the uniform, and the clo-value of total clothing was 0.4–0.6 clo. The uniforms used in this study are lighter than those used in North American and European studies [1, 4–6], because normal wear during the Japanese summer tends to be lighter than the uniform used in those studies.

THERMAL CONDITIONS

Approximating the indoor thermal conditions of summer, the experiments were performed at room temperatures of 26, 28, 30 and 32°C. Mean radiant temperature was equal to room air temperature. Airflow temperatures were equal to air temperature. Subjects

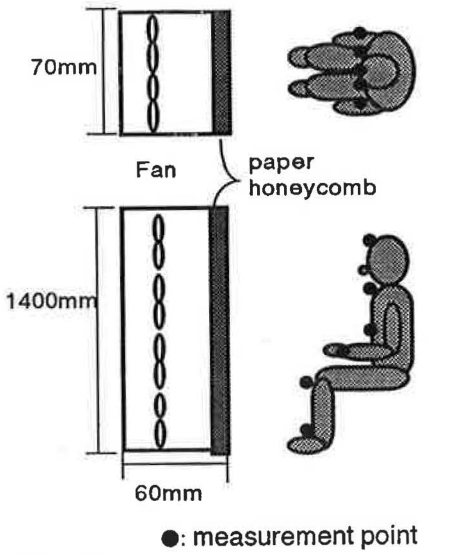

Fig. 1. The airflow apparatus and measurement points.

freely controlled the air velocity themselves for thermal comfort, using a little gear box beside them, but they did not know the velocity they selected. We measured the electric power supplied to the airflow apparatus, and after the experiment we measured air velocity at the locations where the subjects were seated. Figure 1 shows the distance between the airflow apparatus and the subject, and the measurement points of air velocities. The subjects were exposed to a uniform air velocity across the front of the whole body. The turbulence intensity of air velocity was about 5%. The experimental conditions are listed in Table 1, the numbers of subjects exposed to each experimental condition are listed in Table 2, and the physical characteristics of subjects are listed in Table 3.

Measurements

To determine physiological effects, the skin temperatures of subjects at 14 points were measured every 5 seconds by thermocouples (0.1 mm ϕ) fastened to the skin surface by surgical tape. Mean skin temperature was calculated by the weighted mean formula at 12 points' surface area by Hardy and DuBois [7].

To determine psychological effects, the subjects were asked to report general thermal sensations and local thermal sensations for 10 parts of the body using the traditional nine-point scale, and thermal comfort votes using the seven-point scale.

Table 2. numbers of subjects in each thermal conditi

		Air temperature (°C) 26	28	30	32
Experiment 1	30%	—	9	8	—
	50%	4	9	6	—
	80%	4	9	6	—
Experiment 2	Spring	6	7	5	—
	Summer	18	27	19	—
	Autumn	3	5	4	—
	Winter	7	9	7	—
Experiment 3	Old male	—	10	10	10
	Young male	8	8	8	—
	Old female	—	11	11	—

Experimental procedure

Before the experiment each subject was asked two thermal questions. It was ascertained that the subjec had sufficient sleep and normal meals the previous r and had no fever. Uniform and measurement equip were put on in the climate chamber. The subjects st sedentary in the chamber with still air for 60 min Then, remaining sedentary, they controlled air vel freely by themselves for 60 minutes. Figure 2 show experimental schedule.

RESULTS

Differences in preferred air velocity by air temperatur relative humidity (experiment 1)

Figure 3 shows preferred air velocities that were ch by female subjects under muggy conditions. They ferred faster air velocity with increasing air tempera and relative humidity. There are significant differenc preferred air velocity between 30 and 80% RH at 2 The averages of the preferred air velocities at eacl temperature and relative humidity were: 0.53 m/s at : and 50% RH, 0.58 m/s at 26°C and 80% RH, 0.6 at 28°C and 30% RH, 0.87 m/s at 50% RH, 1.02 m 80% RH, 1.06 m/s at 30°C and 30% RH, 1.07 m/ 50% RH, and 1.27 m/s at 80% RH.

Effects of preferred air velocity on skin temperature

Figure 4 shows mean skin temperatures under stil (mean value for the 10 minutes before the subjects b controlling air velocity) and preferred air velocity (n value from 50 to 60 minutes). The mean skin

Table 1. Thermal conditions

	Season	Subject's age	Subject's sex	Air temperature (°C)	Relative humidity
Experiment 1: difference of relative humidity	Summer (29/5–19/7)	Young (21–25)	Female	26, 28, 30	30 50 80
Experiment 2: difference of season	Spring (21/4–7/5) Summer (1/6–15/9) Autumn (19/10–4/11) Winter (9/12–23/1)	Young (21–25)	Female	26, 28, 30	50
Experiment 3: difference of age and sex	Summer (25/7–9/8)	Old (66–79) Young (18–20) Old (66–75)	Male Male Female	28, 30, 32 26, 28, 30 28, 30	50

Table 3. Physical characteristics of subjects

		Number of subjects	Age	Height (cm)	Weight (kg)	Body surface area, As (m^2)	Body mass index, BMI (kg/m^2)
Experiment 1	Young female	10	22.2	159.8	50.3	1.46	19.8
Experiment 2	Spring	7	23.1	156.7	50.7	1.45	20.7
	Summer	23	22.3	158.5	50.5	1.46	20.1
	Autumn	5	22.0	156.0	50.8	1.45	20.8
	Winter	9	22.9	158.8	51.8	1.47	20.5
Experiment 3	Old male	10	72.3	161.7	55.1	1.52	21.1
	Young male	8	19.4	170.5	56.6	1.60	19.5
	Old female	11	71.5	149.5	51.2	1.41	22.5

$As = W^{0.444} \times H^{0.663} \times 88.83$ [12]; BMI $= W/H^2$; W = weight (kg); H = height (m).

peratures increased as the air temperature increased under still air. The mean skin temperatures were 0.3–0.5°C lower when they were exposed to the preferred air velocity than before the subjects controlled air velocity. However, the mean skin temperatures became higher as the air temperature increased. Mean skin temperature was not significantly affected by relative humidity.

Effects of preferred air velocity on thermal sensation and thermal comfort

Figures 5 and 6 show thermal sensation and thermal comfort under still air and under preferred air velocity. In the case of still air the subjects reported being warmer and more uncomfortable, the higher the air temperature and relative humidity. When exposed to preferred air velocity, they mostly reported being slightly cool and comfortable at each air temperature and relative humidity. There is no difference of thermal sensation vote and thermal comfort vote between the three air temperatures and three relative humidities. The subjects were able to make thermally comfortable conditions by controlling preferred air velocity.

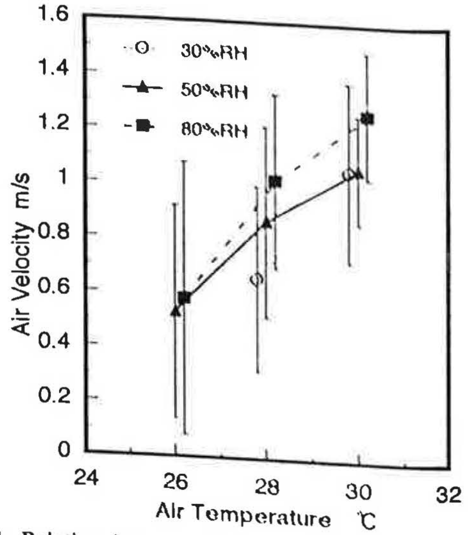

Fig. 3. Relation between air temperature and preferred air velocity. Symbols indicate mean value. Vertical lines indicate standard deviations.

SEASONAL VARIATION OF THE PREFERRED AIR VELOCITY (EXPERIMENT 2)

Figure 7 shows the difference of preferred air velocity for the four seasons. Seasonal variation in preferred air velocity was small. There was a slight tendency to prefer faster air velocity at 28 and 30°C in summer. However, there was no significant difference in preferred air velocity over the four seasons.

Individual variations

Figure 8 shows the frequency of preferred air velocity at every air temperature, and regression lines obtained by the logistic function. The 80% range of preferred air velocity is 0.1–0.86 m/s at 26°C, 0.22–1.28 m/s at 28°C, and 0.68–1.35 m/s at 30°C. The average of preferred air velocity had large standard deviations. The difference of this preferred air velocity is equivalent to an air temperature of 4°C, a very wide range in air-conditioning design.

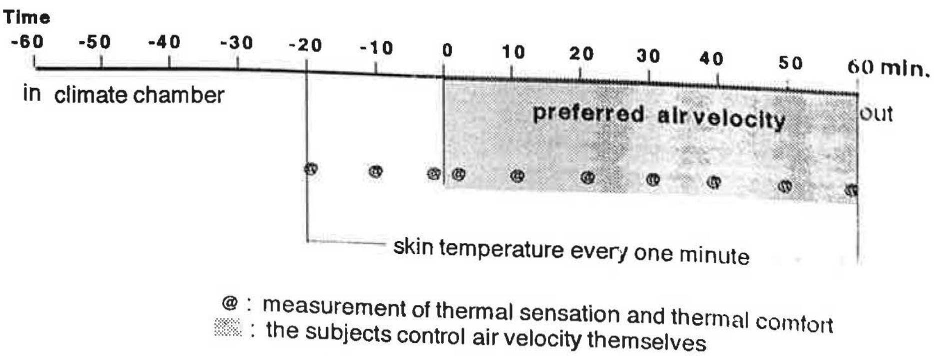

Fig. 2. Experimental schedule.

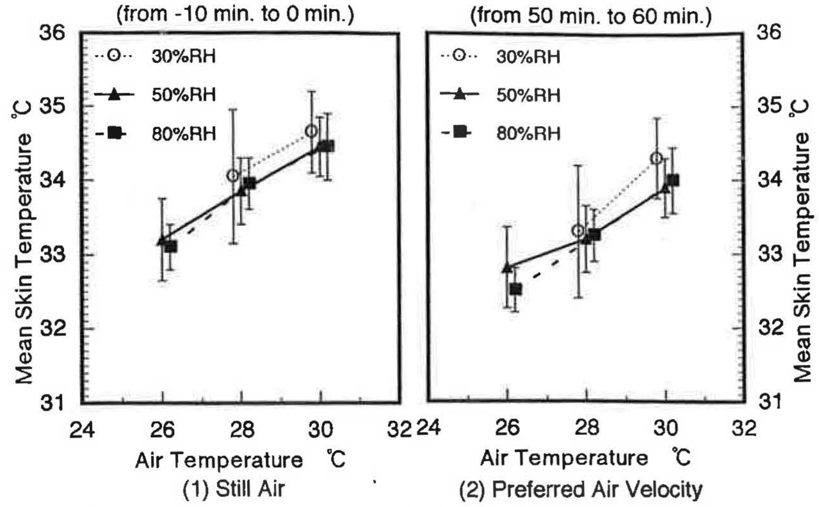

Fig. 4. Relation between air temperature and mean skin temperature. The left chart shows mean value before preferred air velocity and the right chart shows mean value from 50 to 60 minutes exposed to preferred air velocity.

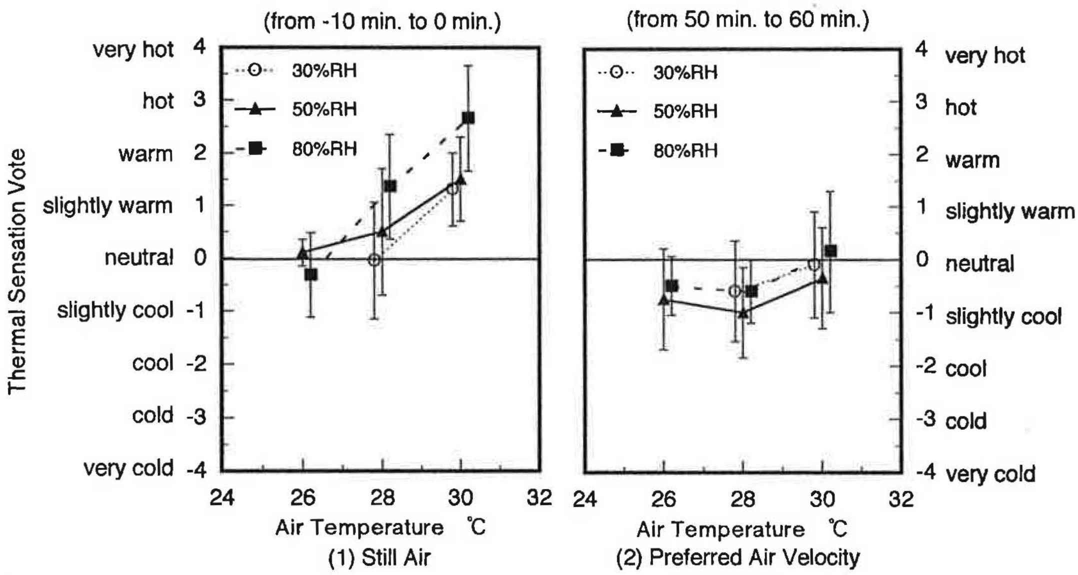

Fig. 5. Relation between air temperature and thermal sensation. The left chart shows mean value before preferred air velocity and the right chart shows mean value from 50 to 60 minutes exposed to preferred air velocity.

We attempted to group subjects by several methods, e.g. "cold-proof", "hot-proof", and by physique. Figure 9 shows the difference in preferred air velocity by cold-proof subjects. The subjects who considered themselves to be strong in the cold preferred faster air velocities. The subjects who reported themselves to be weak in the cold preferred slower air velocities. None of them needed airflow for thermal comfort and stopped the airflow equipment at 26°C. The subjects who reported themselves to be normal in the cold preferred air velocities between those of the weak and the strong subjects. There is no significant difference of physique between the weak subjects and strong subjects. There are however significant differences of preferred air velocity between the weak subjects and the strong subjects, and the weak subjects and the normal subjects. Individual variation is larger than seasonal variation.

DIFFERENCE OF AGE AND SEX (EXPERIME

Figure 10 shows the differences in preferred air ve by age and sex. We used the summer data of exper 2 for the female subjects' data. There is no differe preferred air velocity between male and female su at 26 and at 28°C. Young male subjects preferred air velocities than female subjects at 30°C. The old subjects preferred slower air velocities than the male subjects. The old female subjects preferred fas velocities than the young female subjects.

Figure 11 shows local thermal comfort at preferr velocity. Young male and female subjects felt all parts almost neutral to "slightly cool" at the pre air velocity, but old male subjects felt warmer increasing air temperature. At 30 and 32°C the old subjects felt warm. They could not compensate f

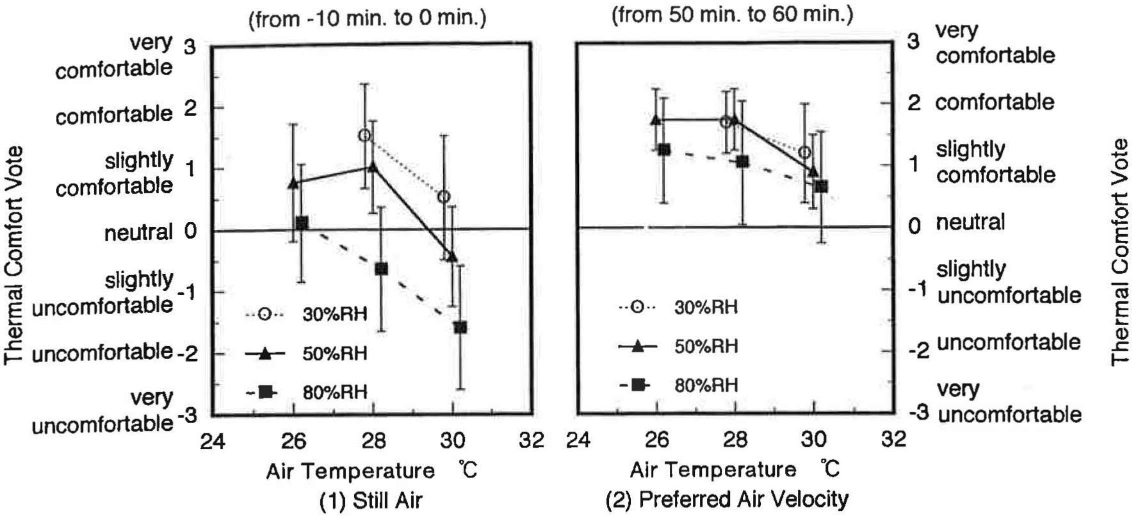

Fig. 6. Relation between air temperature and mean skin temperature. The left chart shows mean value before preferred air velocity and the right chart shows mean value from 50 to 60 minutes exposed to preferred air velocity.

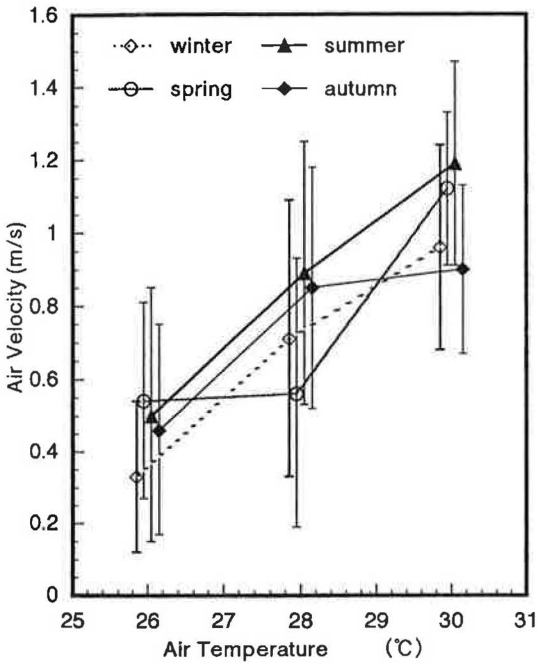

Fig. 7. Difference of preferred air velocity over the four seasons. Symbols indicate mean value and vertical lines indicate standard deviations.

increase of air temperature by increasing air velocity. Old female subjects felt cooler than the young subjects and male subjects. The old female subjects chose very high air velocities.

DISCUSSION

The cooling effects of preferred air velocity on muggy conditions

Figure 12 shows the comparison of preferred air velocity and air velocity predicted by standard effective temperature (SET*) [8] and Fanger's [9] comfort equation. In Tanabe's [2] study at 50% RH, preferred air velocity was higher than in this study. This can be explained by the difference of clo-value, which in Tanabe's study was 0.6 clo, but in this study was 0.3–0.4 clo. In McIntyre's [1] study preferred air velocity was also faster than in this study. We suppose that the reasons depend on the difference of clo-value and air movement. McIntyre used 0.38–0.48 clo and an overhead ceiling fan. The body surface area exposed to air movement from above was small in comparison to that from the front and behind.

The preferred air velocity in this study and both other studies is faster than the air velocity predicted by SET* and Fanger's comfort equation. SET* and Fanger's comfort equation predict air velocity for thermal neutrality. During the experiments on preferred air velocity, the subjects controlled air velocity so that they felt slightly cool, and then they felt comfortable.

Figure 13 shows the relation between SET* and preferred air velocity. The preferred air temperature increased as SET* increased. The regression line shown in Fig. 12 indicates that an increase in mean SET* of 2°C can be compensated for by an increase in air velocity of about 0.2 m/s. Subjects were able to make thermal comfort conditions using preferred air velocity in muggy conditions.

Upper and lower limit of air temperature with preferred air velocity

When the subjects were exposed to preferred air velocity, they mostly reported themselves slightly cool and comfortable in the case of all three air temperatures and humidities. At the higher air temperatures and humidities, the preferred air velocities were faster. However, compared to the exponential relation between air temperature and air velocity in the energy balance equation, the subjects' preferred air velocity is slower at 30°C. At 30°C a few subjects said that they felt uniform airflow with high velocity to be annoying. McIntyre reported that the fan was noisy and air movement was annoying at 28°C [1]. At 30°C thermal sensation and thermal comfort are not at the same levels as at 26 and 28°C, though there is no significant difference in thermal

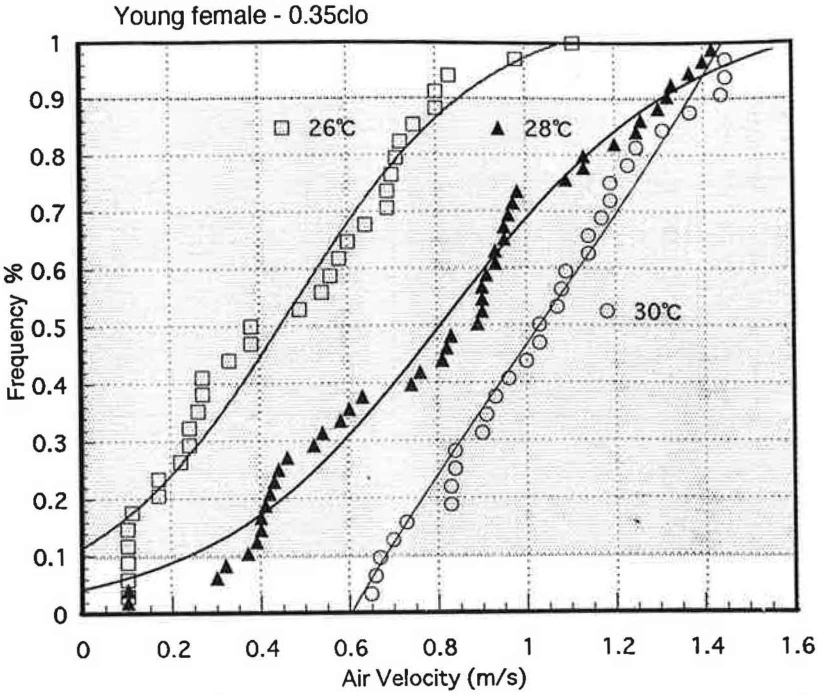

Fig. 8. Frequency of preferred air velocity. Regression lines obtained by the logistic function.

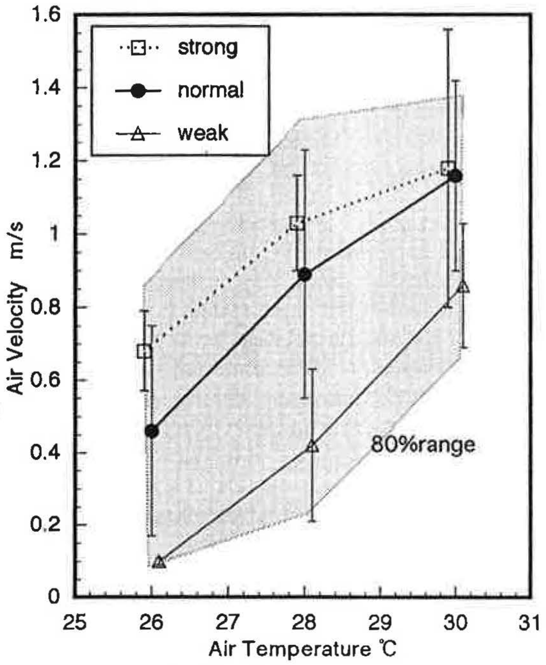

Fig. 9. Difference of preferred air velocity by cold-proofness of subjects. Symbols indicate mean value and vertical lines indicate standard deviation. Shaded area indicates 80% range.

sensation and thermal comfort between 30°C and 26 and 28°C. We suppose that the annoyance of the air velocity prevents the subjects from increasing the preferred air velocity for thermal comfort. Therefore we suppose that an air temperature of 30°C is the upper limit for providing thermal comfort at 0.3 clo. There were no young males annoyed by air movement at 30°C. The males prefer slightly faster air velocity than females, however there is no significant difference in preferred air velocity between males and females.

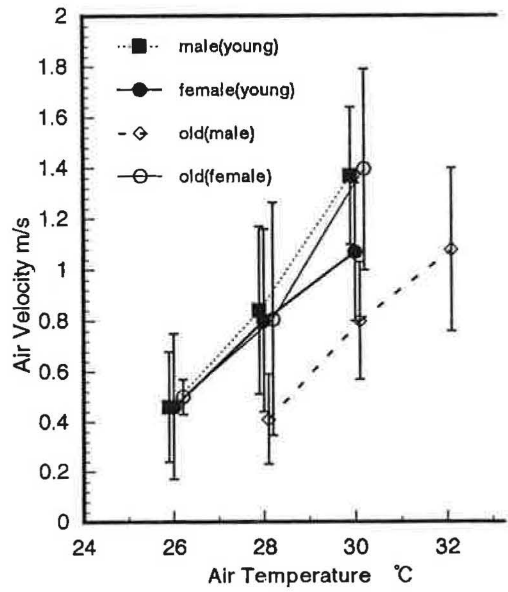

Fig. 10. Differences in preferred air velocity by age a
Symbols indicate mean value and the vertical bars are st
deviation.

The subjects reporting to be weak in the cold d need air movement for thermal comfort at 26° predicted that the subjects reporting to be normal cold did not need air movement at 24°C. We su that an air temperature of 26°C is the lower lin providing thermal comfort at 0.3 clo. We conclud the lower limit of air temperature able to provide th comfort for young subjects with 0.3 clo is 26°C, a upper limit is 30°C.

Preferred air velocity for the old

Tochihara [10] and Ohonaka [11] reported th subjects were not able to regulate thermal conditi

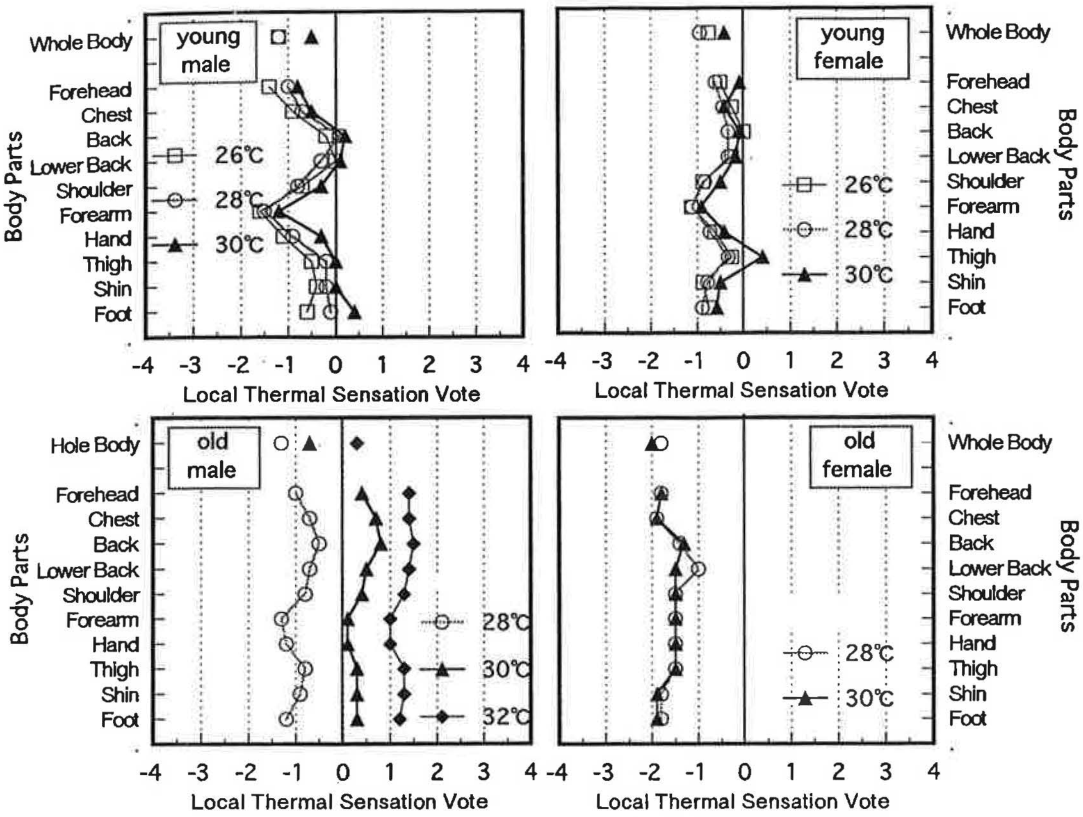

Fig. 11. Local thermal sensation vote.

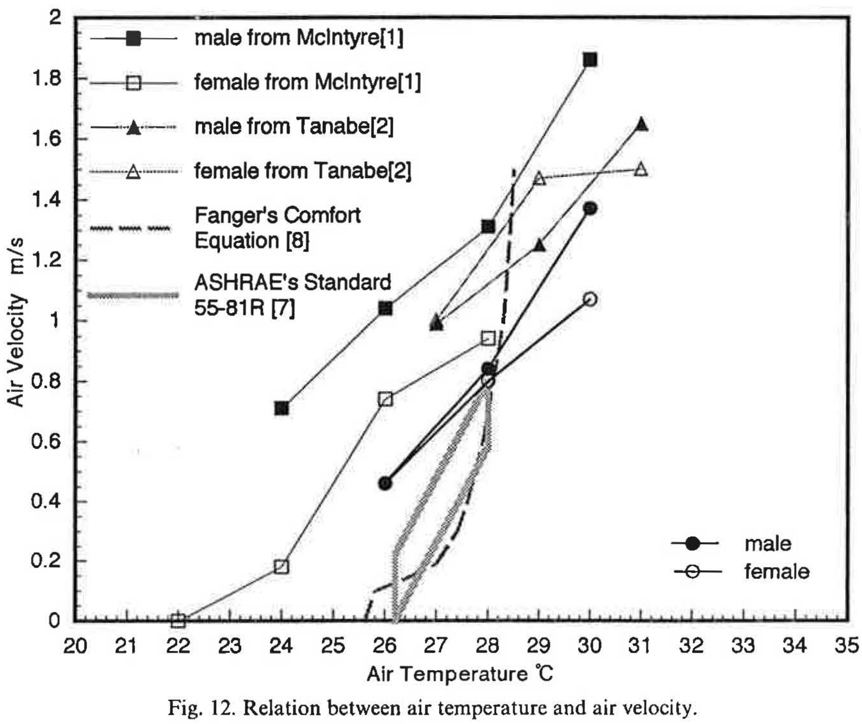

Fig. 12. Relation between air temperature and air velocity.

well as young subjects to provide comfort. In this study old female subjects chose very high air velocities and felt "cool", as shown in Figs 10 and 11. Enomoto [12] reported that the risks associated with the drop in body skin temperature become greater with advancing age in cool conditions. Therefore we recommend that the old control air velocity at values about 0.2 m/s lower than the young at the same temperatures.

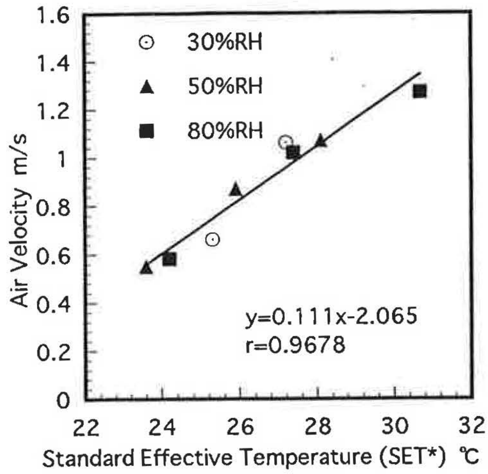

Fig. 13. Relation between standard effective temperature and preferred air velocity. Line is regression line.

CONCLUSIONS

1. The preferred air velocity increased as the air temperature and relative humidity increased. At about 24°C, an increase in SET* of 2°C can be compensated by an increase in air velocity of about 0.2 m/s, sta with an initial value of 0.5 m/s.
2. When exposed to their preferred air velocity, the jects reported themselves slightly cool and com able at each condition, though their mean skin peratures became higher as the air tempera increased.
3. The preferred air velocity was faster than the air ocity predicted by SET* and Fanger's comfort eq tion.
4. For young persons with 0.3 clo, the lower limit o temperature able to provide thermal comfort is 26 and the upper limit is 30°C.
5. Individual variation is larger than seasonal variati The subjects considering themselves weak in the c preferred lower air velocities than did subjects c sidered strong in the cold.
6. There is no significant difference between the f seasons.
7. We recommend that old persons control air veloc at values about 0.2 m/s lower than young persons the same temperatures.

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